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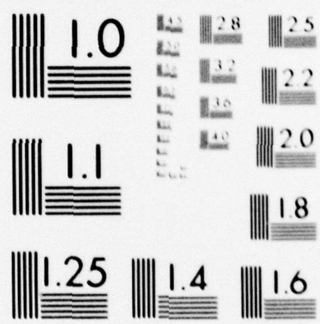
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THREE-DIMENSIONAL BOUNDARY LAYERS ON BODIES OF REVOLUTION AT INCIDENCE

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by

V.C. Patel and B.R. Ramaprian

FINAL REPORT
Grant No. DAAG29-76-G-0036
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Three-dimensional boundary layers, separation, vortices, flow-visualization, boundary layer measurements, calculation methods, laminar and turbulent flow.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This final report summarizes the objectives and accomplishments of an experimental and theoretical investigation of the boundary layer development on bodies of revolution at incidence. The results of the flow visualization studies in laminar flow, detailed measurements in a turbulent boundary layer, and calculations of laminar as well as turbulent boundary layers using two different numerical schemes and turbulence models are reviewed to emphasize the important characteristics of separation in three dimensions. Much of (over)

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the material referred to here will soon be published in the open literature.

I. INTRODUCTION

The problem of calculation of three-dimensional boundary layers and their separation has received increased attention in recent years due to the progress made in the treatment of two-dimensional flows on the one hand, and its importance in practical aerodynamic and hydrodynamic applications on the other. Most of the significant developments in the theory of three-dimensional turbulent boundary layers have taken place in the last two decades and these have been reviewed by Nash and Patel (1972,1976) in general, and by Landweber and Patel (1979) with particular reference to ship hulls. At the time of commencing the study reported here, it was evident that further research was needed in several key areas in order to advance the basic understanding of three-dimensional boundary layers.

The need for a set of detailed and systematic measurements in the boundary layer on a carefully selected configuration was most obvious since the data would provide not only a critical test of the various components of the newer three-dimensional boundary-layer computation procedures but also identify the quantitative features of flow separation. This need has been echoed in several recent survey papers. A review of the existing three-dimensional boundary-layer data has been made by Johnston (1976). Of the nearly eighty sets of so-called three-dimensional measurements examined there, many are restricted to flows whose properties are invariant in one space direction, a majority do not document the most important parameters in sufficient detail, and a very few consider the flow in the neighborhood of truly three-dimensional separations. On the other hand, Smith (1975), Peake (1976) and Wang (1976) have all reviewed three-dimensional flow separation on aircraft, missile and other configurations. From these it is evident that much of the available information has been gathered from flow-visualization studies and is largely qualitative.

The primary objective of the present research was therefore to conduct a detailed experimental investigation in a three-dimensional flow which exhibits the fundamental flow phenomena that are poorly understood at the present time. A body of revolution at incidence was chosen not only becuase it is representative of shapes of practical interest, but also because the boundary layer on it contains most of the complexities encountered in practical situations, such as large and reversing crossflows, viscous-inviscid interactions, onset of open separation and the shedding of longitudinal vortices. A secondary objective was to extend some of the better known and readily available calculation methods to the chosen geometry, and assess their performance relative to the predictions of the overall boundary layer growth as well as separation.

In what follows, the experimental and theoretical studies are described briefly and separately. More detailed information is available in the reports and publications resulting from this project, which are listed in the Appendix, along with the summary of the Grant details.

II. EXPERIMENTAL INVESTIGATIONS

The experimental study was conducted in two phases. Since the choice of a proper shape for the body to be tested in the large wind tunnel of the Institute was not apparent at the outset, it was decided to conduct flow-visualization tests in a water flume and a small wind tunnel in order to explore the overall flow features and identify a shape that would give the most useful data. Upon the successful completion of this phase, detailed pressure distributions and mean-velocity profile measurements were made on a hemisphere-hemispheroid combination body in axisymmetric flow (zero incidence) and at an incidence of 15°. The major results obtained from both series of experiments are summarized below.

A. Flow-Visualization Study

The main objective of this phase of the project was to make a comprehensive visual study of the basic features of the flow past a few representative shapes in order to learn more about separation in three dimensions and, at the same time, to identify the phenomena which should be given special attention in the detailed boundary-layer explorations later on. Although the latter series of experiments was to be performed with Reynolds numbers at which the boundary layer is turbulent, it was felt that the basic features associated with three-dimensional separation would be the same with laminar flow. Consequently, most of the experiments were conducted in water, with models suspended in a hydraulic flume. A series of tests was then undertaken in a wind tunnel at higher Reynolds numbers in order to obtain some information concerning the differences between laminar and turbulent separations.

Since the test procedures and the results are discussed in detail by Han and Patel (1977, 1978), it suffices here to list only the major conclusions of the study:

(a) The experiments provided not only a detailed confirmation of the free-vortex (or open-type) separation and singular (closed-type) separation models of Maskell (1955) and Wang (1972, 1974), but also indicated some additional details which had not been identified before. The color photographs and the movies give a graphic description of the events leading to three-dimensional flow separation at various incidences.

(b) Although the precise locations of the lines of separation depend on the body shape, angle of attack and Reynolds number (i.e., whether the boundary layer is laminar or turbulent), the basic features of the flow in the neighborhood of such separations, when they occur, appear to be independent of Reynolds number.

(c) Comparisons made between the results of the flow-visualization experiments on a spheroid and the laminar-flow calculations of Wang (1972, 1974) indicated qualitative agreement. The quantitative differences were attributed to viscous-inviscid interactions and the occurrence of secondary separation and reattachment, which could not be treated in the calculations.

(d) Of the three bodies examined, the combination body, made up of a hemispherical nose and a hemispheroidal rear, was found to be the most suitable for making further boundary-layer measurements.

B. Detailed Measurements in the Boundary Layer

A large-scale model (length=1.37m, maximum diameter=0.343m) of the combination body mentioned above was constructed and tested in the largest (1.67m octagonal working section) wind tunnel of the Institute at a length Reynolds number of 2.3×10^6. The details of the model construction, instrumentation, experimental procedures and results are given in Ramaprian, Patel and Choi (1978). The following is the abstract of that paper:

"An experimental study of the three-dimensional turbulent boundary layer on a body of revolution is reported. The data correspond to axisymmetric flow as well as the flow at an angle of incidence of 15 degrees, and include surface pressure distributions and the distribution of the magnitude and orientation of the velocity vector in the boundary layer. The results clearly exhibit most of the complexities encountered in practical three-dimensional boundary-layer-flow situations, such as viscous-inviscid interaction, reversal of crossflow, open separation and onset of longitudinal vortices. Major implications of these results on the development of computation procedures are discussed."

Among the major conclusions of this phase of the investigation are the following:

(a) The experimental results clearly demonstrate the complexities of the three-dimensional boundary layer on a body of revolution at incidence. The present experiment differs from previous investigations insofar as it also provides quantitative information on some of the extreme features of a three-dimensional boundary layer. For example, here we have the case of a boundary layer whose growth in the transverse direction is more spectacular than in the longitudinal, primary direction. Inspite of the zero-crossflow constraint imposed by the plane of symmetry, the boundary layer accomodates large and reversing crossflows over a significant portion of the body. Other, intricately related features include the development of a vortical structure within the boundary layer, and the presence of a large region of strong viscous-inviscid flow interaction even in the absence of any catastrophic breakaway (separation) of the viscous flow from the surface. To be sure, many of these phenomena have been observed in previous experimental studies (largely through flow-visualizations on aircraft and missile configurations) and some have been predicted by numerical solutions restricted to laminar flow. However, the present data document these in some detail and would prove valuable not only in the general understanding of three-dimensional turbulent boundary layers but also in guiding the development of appropriate methods of prediction of such flows.

(b) In a series of papers, Wang (1970, 1972, 1974a,b,c, 1975) has presented the results of numerical solutions of the laminar boundary layer on a 4:1 spheroid at several incidences. Although the present experiment is concerned with turbulent flow and quite different geometry, the data qualitatively confirm some aspects of his results. These include the differences between the flows in the leeward and windward sides of the plane of symmetry as well as the reversal of the circumferential component of velocity or wall shear stress along a well defined line on the body.

(c) As indicated earlier, one of the objectives of the present experiment was to study the characteristics of the boundary layer in the neighborhood of what Wang has termed an open separation. Inspite of the fact that the present flow is turbulent and the body geometry is different, it was hoped that the data would indicate the quantitative features of the flow that lead to the formation of an open separation line. Examination of the various views of the data suggests the beginning of a vortex structure but not any breakaway of the flow from the surface, (at least in the region covered by the measurements), as implied by the open separation concept. It is possible that the flow leaves the surface downstream of the region of measurement. This is perhaps a fortunate coincidence, since the data over such a large area of the body correspond to an unseparated flow and consequently may be used to test boundary-layer like calculation methods in which due account is taken of the viscous-inviscid interaction associated with the local thickening of the boundary layer and the formation of an embedded vortex-like flow.

III. THEORETICAL INVESTIGATIONS

This phase of the study involved the development and assessment of calculation procedures for three-dimensional laminar and turbulent boundary layers on bodies of revolution at incidence and has been conducted in parallel with the experimental investigations. Some aspects of the study will be reported in a paper under preparation (Patel and Choi, 1978) and further details will be included in the Ph.D. dissertation of Choi (1978). The following is part of an extended abstract of the paper:

"The prediction of the development of the boundary layer, whether laminar or turbulent, on bodies of revolution at incidence represents a severe test of any calculation procedure since the flow is characterized by the occurrence of large crossflows, the reversal of the circumferential flow over some part of the surface, localized thickening of the boundary layer, formation of longitudinal vortices within the boundary layer which eventually lead to a free-vortex or open separation, and strong interaction between the viscous and inviscid flows. This paper describes the results of a numerical study designed to explore the performance of some currently available three-dimensional boundary-layer calculation procedures when applied to bodies of revolution at incidence.

The method of Chang and Patel (1975), designed originally for ship hulls, and that of Nash and Scruggs (1977), developed for finite wings, have been modified to perform calculations on axisymmetric bodies in body-fitted cylindrical polar co-ordinates. These methods differ substantially in their numerical content since the former is of the Crank-Nicolson type while the latter employs an alternating-direction-implicit (ADI) procedure. Furthermore for turbulent flow, they employ quite different closure models (eddy-viscosity in the former, and turbulent kinetic-energy equation in the latter). Consequently, comparative calculations enable the evaluation of the relative merits of the numerical techniques as well as the turbulence models.

In laminar flow, the two methods have been used to calculate the boundary layer on a 4:1 prolate spheroid at a low (6 degrees) and a high (30 degrees) incidence. The results are compared with those obtained earlier by Wang (1970, 1974, 1975) by yet another numerical method. It is shown that all methods give quite similar results in the region where the crossflow is unidirectional, i.e., in the region between the windward symmetry plane and the line on the body which indicates the reversal of the circumferential component of velocity or wall shear stress. Figure 1 shows the predicted position of this line at $\alpha=6°$ and $30°$. Notice that all three predictions are in reasonable agreement with one another. At the lower incidence, Wang (1975) was able to obtain a solution also on the leeward side, beyond the line of circumferential flow reversal, by a careful modification of his numerical scheme (advancing toward the windward side from the leeward plane of symmetry, along which an independent prior solution can be obtained). Such a solution has not, however, been reported for the larger incidence. The method of Chang and Patel could also be modified, at least in principle, to perform similar calculations. However, such a procedure is not altogether satisfactory since the treatment of the boundary layer in the neighborhood of the circumferential flow reversal line leads to ambiguities. Since the flow on either side of this line comes entirely from upstream, it should be possible to obtain an unified solution over the region between the leeward and windward symmetry planes, including the location of the line itself. It is shown that the ADI method encounters no special difficulty since it uses locally upwind differences and performs a simultaneous solution over the entire circumferential domain. Figure 2 shows typical results obtained at an axial location where the circumferential flow is reversed over a large part of the body. The thickening of the boundary layer in the neighborhood of the circumferential flow reversal point and the emergence of a vortex-like structure embedded within the boundary layer are evident from this figure. These and other features of the flow are discussed in the paper...."

Calculations similar to those mentioned above are being made for the turbulent boundary layer on the combination body tested in the present research project. This effort is continuing and the results will be reported in Patel and Choi (1978) and Choi (1978).

IV. CONCLUDING REMARKS

This report summarizes the accomplishments of the research performed during the period September 1975-August 1978 under AROD Grant DAAG29-76-G-0036. Two aspects of the project are continuing beyond the grant period: (a) the computation of turbulent boundary layers, and (b) further measurements of the boundary layer on the combination body at a smaller (8 degree) incidence. The former could not be completed due to the increased emphasis placed on the thorough validation of the computation procedures in laminar flow. On the other hand, the desirability of obtaining data at a smaller angle of attack became apparent from the flow complexities observed in the experiments at 15° incidence. However, it is expected to complete these investigations by the end of 1978. The results will be described in subsequent publications. The publications resulting from this project also describe the needs for additional experimental and theoretical research.

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APPENDIX: General Information on Grant

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   Proposal: AMXRO-EG-13054
   Grant: DAAG29-76-G-0036
   Period: September 1975 - August 1978
   Title: Three-Dimensional Boundary Layers and the Origin of Lift on Bodies of Revolution at Incidence

2. Scientific Personnel Supported:
   Dr. V.C. Patel, Professor, Co-Principal Investigator
   Dr. L. Landweber, Professor, Co-Principal Investigator
   Dr. B.R. Ramaprian, Assoc. Professor, Research Scientist
   Mr. T. Han, Graduate Research Assistant
   Mr. D.H. Choi, Graduate Research Assistant

3. Advanced Degrees Earned:
   T. Han, M.S. with thesis entitled "A Flow-Visualization Study of Three-Dimensional Boundary-Layer Separation on Bodies of Revolution at Incidence," May 1977.

   D.H. Choi, Ph.D. dissertation entitled "Boundary Layer on a Body of Revolution at Incidence," to be submitted Dec 1978.

4. Technical Reports and Manuscripts Submitted or Planned for Publication

   T. Han and V.C. Patel, "Flow-Visualization of Three-Dimensional Separation on Bodies of Revolution at Incidence," Iowa Institute of Hydraulic Research, The University of Iowa, IIHR Report 205, June 1977, 69 p.

   T. Han and V.C. Patel "Flow Separation on a Spheroid at Incidence," Submitted to J. Fluid Mech., Nov 1977, accepted for publication.

   B.R. Ramaprian, V.C. Patel, and D.H. Choi, "Mean-Flow Measurements in the Three-Dimensional Boundary Layer Over a Body of Revolution at Incidence," to be submitted to J. Fluid Mech, Oct 1978.

   V.C. Patel and D.H. Choi, "Calculation of Three-Dimensional Laminar and Turbulent Boundary Layers on Bodies of Revolution at Incidence," under preparation, to be submitted for presentation at 2nd International Symposium on Turbulent Shear Flows, London July 2-4, 1969, and for publication, Dec 1978.